Computer Integrated Simulation of Geometric Features in 3 Axis Coordinate Measuring Machines

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Abstract

A comprehensive computer software has been implemented in conjunction with the software for volumetric error generator, to assess simulation on specific measurement tasks. The simulation algorithms have been developed for major measurement tasks, such as step gauge, ring gauge, sphere gauge, and cylinder gauge simulations etc. Verification and practical applications of the developed module have shown its efficiency and validity.

1.Introduction

Coordinate measuring machine(CMM) plays more increasing roles as a measurement equipment or measurement centre for the quality control in industry, where calibration, verification, and compensation if necessary, are vital for the machines in order to maintain high standard of performance. In view of these, many articles have been published on the verification, calibration, compensation of CMMs,etc.(e.g.[1],[2],[3],[4]). In the other hands, when the error informations on a CMM are known,the influences of the machine errors on some specific measurement tasks such as step gauge measurement are not known yet in detail, as thorough analysis is virtually impossible by practical measurement due to lots of measuring lines to be covered in a working volume of the machine. Therefore a computer module has been desirable to assess numerical simulation on specific measurement tasks such as step gauge measurement,etc.. In this paper a comprehensive computer software has been implemented, in conjunction with a software for volumetric error generation([5]), performing numerical simulation on geometric features such as step gauge, ring gauge, sphere gauge, and cylinder gauge, etc. Verification and two cases of practical applications to commercial CMMs in current use have proved the efficiency and validity of the developed system.

2. Step Gauge Simulation

Step gauge is one of simple,useful equipments for assessment of accuracy, thus many national standards such as British Standards and German standards adopt the step gauges for verification of CMMs. When volumetric error informations(volumetric error map) are available, it is possible to simulate the step gauge measurement,i.e., length measurement uncertainty.

2.1 Length uncertainty and volumetric errors

When the volumetric error map has been constructed at all nominal nodes of fixed interval, the volumetric error components (X,Y, and Z components) can be evaluated at any intermediate positions within a working volume with the aid of developed volumetric interpolation technique([6]).

Let $(\Delta X_1,\Delta Y_1,\Delta Z_1)$ be the volumetric error at $P_1(X_1,Y_1,Z_1)$ position, and $(\Delta X_2,\Delta Y_2,\Delta Z_2)$ be that at $P_2(X_2,Y_2,Z_2)$, respectively. The length measurement error, DE, between the two points is,

$$\Delta E=((\Delta X_2,\Delta Y_2,\Delta Z_2)-(\Delta X_1,\Delta Y_1,\Delta Z_1))\ (e_1,e_2,e_3)$$

$$=(\Delta X_2-\Delta X_1)e_1+(\Delta Y_2-\Delta Y_1)e_2+(\Delta Z_2-\Delta Z_1)e_3$$

where e_1, e_2, e_3 are the components of unit vector from P_1 to P_2 points.

When the length measurement errors are evaluated at various length intervals, it is possible to plot a graph of error vs. nominal length, displaying the simulated length measurement error at every length interval.

2.2 Evaluation of length uncertainty curve

Generally([1],[3]), the uncertainty of length measurement can be defined as a linearised curve, that is, $U=A+KL\leq B$, where U is the uncertainty of length measurement, L is the measuring length, and A,K,B are constants to be evaluated. In this developed module, a new method has been proposed and implemented to evaluate the slope K; least squares slope over all data, and least squares slope over maximum error data (data of "envelope" points). The former is to evaluate the least squares slope considering all the data in the error vs. length nominal plot. The latter is identical to the former except that it considers the maximum data("envelope" point data) at every nominal length. In both cases A term can be determined as maximum intercept by shifting the evaluated best fit line, so that the shifted straight line may contain all the error data in the plot. B term is then the maximum boundary of the error in the error vs. nominal length plot.

2.3 Length uncertainty along measuring lines

Representative measuring lines

Many national standards such as BS and VDI/VDE recommend some representative measuring lines for the step gauge assessment,for example, BS 6808 recommends 4 space diagonals, 3 in-plane diagonals, and 1-in line diagonal for the 3D length uncertainty measurement. In the developed module, several cases of length uncertainty are implemented, where 13 measuring lines(4 space diagonals, 6 in-plane diagonals,3 in-line diagonals), 8 measuring lines (4 space diagonals, 3 in-plane diagonals, 1 in-line diagonal), and 4 measuring lines (4 space diagonals) are considered. In addition, any specific measuring lines can be considered for the length uncertainty.

All possible measuring lines

It is one of main advantages that the developed module can assess the length measurement error along all possible measuring lines, which is not possible in the practical measurement of step gauges in CMMs. For all possible 3D measuring lines, all possible sets of two points whose position vector from one to the other is 3 dimensional are considered, constructing all possible volumetric grids within the working volume. 4 space diagonals are assessed to evaluate the length uncertainty, maximum error value is then chosen and stored for the specific measurement length. The length uncertainty curve is then calculated from the stored data, giving A,K, and B values with the plot of error vs. measurement length. Similarly, all possible sets of two points whoso position vector is 2 dimensional are considered for all possible 2D measuring lines. When two points are chosen, 2 planar diagonals are considered to evaluate the length uncertainty. Also, all 1D measuring lines are assessed to evaluate the length uncertainty.

Randomly chosen measuring lines

Great number of measuring lines have to be assessed for the all possible measuring lines, for example, 7 X 7 X 7 grid configuration requires about 58000 measuring lines ($\simeq {}_{7x7x7}C_2$) to be assessed, taking about 30 min in PC environment. Therefore it was desirable to choose less measuring lines, still giving close length uncertainty values to those of all possible measuring lines. Random number generation module has been developed and incorporated, into the selection of measuring lines within the working volume. When total number(N) of measuring lines to be assessed is given, 6 6 times the total number of random values(6N) are generated using the developed module of pseudo random number generator, giving each 3N numbers for P1,P2 points. Thus, the length uncertainty curve is calculated and plotted for the random measuring lines.The practical comparison between the all possible measuring lines and randomly chosen measuring lines is made and discussed in later section.

2.4 Error representation

The evaluated step gauge simulation is graphically displayed on computer screen. The error vs. nominal length plot is made with various symbols and colors depending on the measuring lines.

3.Ring gauge simulation

As one of simulations on geometric features, ring gauge simulation has been developed. After the volumetric error map has been constructed over a working volume, the CMM measurement can be simulated for a ring gauge located within the working volume. Let $(\Delta Xc,\Delta Yc,\Delta Zc)$, $(\Delta X,\Delta Y,\Delta Z)$ be the volumetric error data at points C (Xc,Yc,Zc), $P(X,Y,Z)$, respectively, where C is the centre point of the ring gauge and P is a measuring point along the ring gauge. Thus, the error in ring gauge measurement,RE, is

$$RE=((\Delta X,\Delta Y,\Delta Z)-(\Delta Xo,\Delta Yo,\Delta Zo))\ n$$

$$=(\Delta X-\Delta Xo)nx+(\Delta Y-\Delta Yo)ny+(\Delta Z-\Delta Zo)nz$$

where $n(nx,ny,nz)$ is the radial vector from C position to P position, varying position to position, that is,

$nx=(X-Xo)/R$

$ny=(Y-Yo)/R$

$nz=(Z-Zo)/R$

where R is the nominal radius of the ring gauge.

XY, YZ, or ZX plane can be chosen as the reference plane on which the ring gauge is located, and the centre coordinate and nominal radius of the ring gauge are inputted through the key board. As results, maximum and minimum radii are calculated, giving radial bandwidth for the ring gauge. Practical assessments will be mentioned in later sections.

.2 Error representation

The calculated ring gauge errors are then graphically displayed, showing nominal, maximum, and minimum radii. The bandwidth is evaluated and displayed as the differences between the maximum and minimum radii. Practical assessments will be mentioned in later sections.

4. Sphere gauge simulation

Spheres are frequently used in the stage of verification, and it is worth while to simulate sphere gauge in a specific CMM, whose volumetric error data are known. The developed simulation module for sphere gauge begins with updating the machine specification, such as machine type, initial positions, step size etc, then followed by the input procedures for sphere radius, centre coordinate, the number of steps in longitudinal and circumference direction. The volumetric error data are then assessed through the volumetric interpolations and the sphere error at each spherical point can be obtained. Let $(\Delta Xc,\Delta Yc,\Delta Zc)$,$(\Delta X,\Delta Y,\Delta Z)$ be the volumetric error components at C(Xc,Yc,Zc) and P(X,Y,Z) points in the working volume, where C is the centre coordinate and P is a point on the sphere gauge. The error in sphere measurement, SE, is

$$SE=((\Delta X,\Delta Y,\Delta Z)-(\Delta Xc,\Delta Yc,\Delta Zc))\ N$$

$$=(\Delta X-\Delta Xc)Nx+(\Delta Y-\Delta Yc)Ny+(\Delta Z-\Delta Zc)Nz$$

where Nx,Ny,Nz are components of unit vector n from point C to point P, that is

$$Nx=(X-Xo)/R$$

$$Ny=(Y-Yo)/R$$

$$Nz=(Z-Zo)/R$$

where R is the radius of the sphere.

4.2 Error representation

The calculated sphere errors are then displayed 3 dimensionally in the computer screen, giving the centre coordinates, number of vertical and horizontal steps, nominal radius, maximum radius, and minimum radius. The bandwidth is calculated as the difference between the maximum and minimum radii. Practical assessment results will be mentioned in later sections.

5. Cylinder gauge simulation

The cylinder gauge simulation has been also implemented, as it would be relevant when a series of ring gauge simulations are performed, or a real cylinder gauge is probed inworking volume of a CMM.

Cylinder geometry

A cylinder can be characterised in 3D space by basic geometric factors such as radius(R), length(L), and bottom coordinate(B). When the cylinder is inclined from horizontal and vertical axes, coordinate transformations are required. A cylinder geometry is shown in fig.1 , where θ,ϕ are inclination angle from X, Z axis,respectively. Then, a transformation matrix, T, can be defined in order to transform the coordinates

$$T=\begin{bmatrix} \cos\phi\cos\theta & -\sin\theta & \cos\phi\sin\theta \\ \sin\phi\cos\theta & \cos\phi & \sin\phi\sin\theta \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

such that [OX'Y'Z']=T[OXYZ] where [OX'Y'Z'] is new coordinate data (transformed), and [OXYZ] is old coordinate data.

In practice, the inclination angle,ϕ,θ can be calculated from the position vector of the cylinder axis(longitudinal axis).

After the cylinder informations such as radius, bottom coordinate, length, position vector of cylinder axis, number of sampling steps in longitudinal and circumference direction, are inputted to the system, the cylinder geometry is numerically formed in the developed system. Then error simulations are followed, radial error and axial error.

5.2 Radial error simulation

The radial error in the cylinder measurement can be evaluated as vectorial comparison of volumetric errors between bottom point and all points on the cylinder, which is to be decomposed into radial direction.

Let $B(X_B,Y_B,Z_B)$,$P(X,Y,Z)$ be the coordinate of bottom and measurement point; $(\Delta X_B,\Delta Y_B,\Delta Z_B)$,$(\Delta X,\Delta Y,\Delta Z)$ be volumetric errors at B,P points, respectively.

The radial error,RADIAL_ERROR, is

$$RADIAL\_ERROR=((\Delta X,\Delta Y,\Delta Z)-(\Delta X_B,\Delta Y_B,\Delta Z_B))\ R$$

$$=(\Delta X-\Delta X_B)Rx+(\Delta Y-\Delta Y_B)Ry+(\Delta Z-\Delta Z_B)Rz$$

where Rx,Ry,Rz are components of unit vector,R, in radial direction, that is,AP direction, in fig.1 .

5.3 Axial error simulation

When a real cylinder is assumed to be assessed in the working volume of CMM, it is useful to have information on axial component of cylinder simulation at normal surfaces to the cylinder, such as end surfaces. The axial error can be obtained similarly from the vectorial calculation of the volumetric errors between the bottom point and a measuring point, which is to be decomposed into the axial direction.

The axial error, AXIAL_ERROR, is

$$AXIAL\_ERROR = ((\Delta X, \Delta Y, \Delta Z) - (\Delta X_B, \Delta Y_B, \Delta Z_B))\ L$$

$$= (\Delta X - \Delta X_B)L_x + (\Delta Y - \Delta Y_B)L_y + (\Delta Z - \Delta Z_B)L_z$$

where L_x,L_y,L_z are components of the unit vector,L, along the length direction.

5.4 Error representation

The calculated radial errors are then 3 dimensionally displayed on the computer screen, showing error cylinder as well as original cylinder. Maximum,minimum radii are evaluated and the radial cylinder error is calculated as the bandwidth of the maximum and minimum radial errors. Similarly, axial errors are displayed, giving axial error distribution along circumference. The maximum,minimum errors, thus bandwidth are calculated, and displayed.

6.Practical assessments

To prove validity and efficiency of the developed module for numerical simulation on geometric features, two cases of synthesis data are considered for verification; two cases of practical simulation based on the measured parametric errors are performed.

6.1 Verification

It is important to verify that the developed system can properly simulate practical measurement. A set of synthesis data of pure geometric error are provided to the system, and geometric simulation such as step gauge, ring gauge, sphere gauge, and cylinder gauge are simulated and compared with the expected results. The type of the

CMM is assumed as the moving bridge.

(1) Pure positional error (file name:exx)

Assume that only X positional error is existing as in fig.2a, namely, 20μm bandwidth over 200 mm span, while all other error components are assumed zero. The step gauge simulation is shown in fig.2b, which is tested along the (0,0,0)-(200,0,0) measuring line. The result is is identical to the given X positional error. The ring gauge simulation is performed, whose centre coordinate is (100,100,1), located on the XY plane. The nominal radius of the ring is 40 mm, 200 points being considered along the circle. The simulation result is supposed as elliptical shape and shown in fig.2c, giving 4 μm bandwidth over the ring. Similarly, cylinder gauge simulation can be assessed,(100,100,1) centre coordinate, 40mm radius, 90mm cylinder length, being located vertically. 10 steps and 200 points are considered along the cylinder axis and circumference. Fig.2d shows the cylinder simulation, giving 4 μm bandwidth. Fig.2e shows the sphere gauge simulation, whose centre coordinate is (100,100,50), 40mm radius. 15steps and 200 points are considered along the vertical, circumference directions, respectively, giving 4 μm sphere error.

(2) Pure squareness error (file name:eco)

As another simple geometric case, assume that only squareness error between X and Y axes is present, whose value is 25 μm/m out of squareness), while all the other parametric error components are zero. The step gauge simulation is performed, and fig.3a shows the step gauge simulation along 4 space diagonals, where effect of the squareness can be clearly shown. Fig.3b shows the ring gauge simulation, (100,100,50) centre coordinate, 40 mm radius, located on the XY plane. The simulation result is elliptical form, which is similar to Knapp's note([7]), giving 1 μm bandwidth. The cylinder simulation is performed, and shown in fig.3c. The bottom coordinate is (100,100,0), 40 mm radius,100 mm length, which is located vertically on the XY plane. The bandwidth(cylinder error) is 1.0μm, like ring gauge simulation. The sphere gauge is also simulated, and is shown in fig.3d. The centre coordinate is 9100,100,50), 40 mm radius, about 1μm (0.994 μm) bandwidth around the gauge, giving ellipsoidal form as expected.

6.2 A CMM at GEC,Preston

A CMM at GEC, Preston, was chosen for the practical assessment, as some parametric error calibration data were available([8]). The CMM was moving horizontal type, and the size for working volume of 900 mm X 575 mm X 400 mm
(18 steps X 23 steps X 16 steps) was considered. Fig.4a shows the volumetric error map of the machine, where length measurement errors are evaluated along 4 space diagonals; diagonal 1 is from (0,0,0) to (Xmax,Ymax,Zmax),
diagonal 2 is from (Xmax,0,0) to (0,Ymax,Zmax)
diagonal 3 is from (0,Ymax,0) to (Xmax,0,Zmax)
diagonal 4 is from (0,0,Zmax) to (Xmax,Ymax,0), and Xmax,Ymax,Zmax are the maximum nominal coordinate of the considered working volume.

Step gauge simulation

The step gauge simulation has been performed along some representative measuring lines; 4 space diagonals, 8 measuring lines (BS 6808), 13 measuring lines are assessed for the length uncertainty. Also, all possible 3D, 2D, and 1D measuring lines are assessed in the working volume. In addition, 100, 500, and 1000 measuring lines are randomly chosen by the developed random number generation module. The results are as follows, where a reduced working volume (7 X 7 X 7) has been considered for saving running time.

4 space diagonals	55.3 + L / 24.9 <= 117.9
8 measuring lines(BS6808)	58.2 + L / 26.5 <= 117.0
13 measuring lines	59.8 + L / 27.4 <= 116.7
ALL 3D measuring lines	80.0 + L / 18.0 <= 166.6
ALL 2D measuring lines	82.2 + L / 162.4<= 91.8
ALL 1D measuring lines	45.0 + L / 47.0 <= 78.1
100 lines	47.0 + L / 15.5 <= 147.3
500 lines	55.1 + L / 15.9 <= 152.7
1000 lines	62.5 + L / 16.1 <= 159.2

It is interesting to note that 3D length uncertainty along representative measuring lines is much less than that along all possible 3D measuring lines in the working volume. As an example, fig.4b shows the 3D length uncertainty along 4 space diagonals with 100 mm step size, where the diagonal 1 to 4 correspond to those defined in the above volumetric error map.

Ring gauge simulation

Ring gauge simulation has been also performed. Fig.4c shows a ring gauge simulation, whose centre coordinate is (900,600,600), located on the XY plane. 200 points are simulated along the circumference of the ring gauge, whose radius is 100 mm. The ring gauge simulation gives 23.75 μm bandwidth.

Sphere gauge

Fig.4d shows a sphere gauge simulation, whose centre coordinate is (900,600,600), with 15 vertical steps, 200 simulation points along the circumference. When the nominal radius is 100 mm, the maximum, and minimum error in the radius are 16.4 μm, -11. μm, giving 28.3 μm bandwidth. In fig.4d, the reference radius OX indicates the reference line, from which the angle θ is made. The error sphere as well as nominal sphere are shown.

Cylinder gauge simulation

Fig.4e shows a cylinder gauge simulation (radial error). The bottom coordinate is assumed as (900,600,100), 400 mm cylinder length, 100 mm cylinder radius. 10 steps are considered for the cylinder axis direction, and 200 points are considered for the circumference direction, and the cylinder is supposed to be stand vertically. In fig.4e, radial error along the cylinder gauge is calculated and displayed, giving 176.34 μm as bandwidth (cylinder error). Fig.4f shows the axial error simulation along the bottom surface of cylinder, giving 10.56 μm bandwidth.

6.3 A CMM at NPL, Teddington

As another practical assessment, a CMM at NPL, Teddington was chosen, which was moving bridge type, and the size of working volume was 900mm X 575 mm X 400 mm (18 step X 23 steps X 16 steps). Fig.5a shows the volumetric error map, giving -24.0 μm, 21.3 μm, 25.9 μm, -35.9 μm, along diagonal 1 to 4 , respectively.

Step gauge simulation

Step gauge simulation has been performed in various ways.For example,Fig.5b shows a step gauge simulation along 4 space diagonals as measuring lines. 50 mm step size was chosen and the length uncertainty curve is evaluated as 27.0 + L / 45.5 <= 52.1 μm. For the assessment of all possible measuring lines, a reduced working volume (7 step X 7 step X 7 step) was chosen, and step gauge simulation has been performed along all possible measuring lines and randomly selected measuring lines. The results are as follows;

4 space diagonals	18.9 + L / 61.0 <= 24.9
8 measuring lines (BS6808)	19.0 + L / 62.0 <= 24.9
13 measuring lines	19.2 + L / 66.7 <= 24.7
ALL 3D measuring lines	26.9 + L / 62.1 <= 32.8
ALL 2D measuring lines	22.4 + L / 162.4 <= 24.6
ALL 1D measuring lines	19.0
100 random measuring lines	20.1 + L / 35.1 <= 30.6
500 random measuring lines	23.0 + L / 31.1 <= 34.8

1000 random measuring lines 23.7 + L / 34.3 <= 34.4

Similarly, it is noteworthy to mention that the length uncertainty values along some representative measuring lines are much less than those along all possible 3D measuring lines, and a number of randomly chosen measuring lines can give the values of length uncertainty which is close to the all 3d measuring lines.

Ring gauge simulation

Fig.5c shows a ring gauge simulation, whose centre point is (450,280,100) in the working volume, located on XY plane. The ring of 150 mm radius has been considered, with 200 sampling points along the ring circumference. In fig.5c, maximum and minimum radii are 150.009 mm, 149.989mm, giving 19.49 μm bandwidth

Sphere gauge simulation

Fig.5d shows a sphere gauge simulation, whose centre point is (450,280,200) in the working volume. 15 steps, 200 sampling points are considered for the vertical and circumference direction, respectively. The sphere gauge of 150 mm radius has been considered, giving 39.34 μm bandwidth.

Cylinder gauge

Fig.5e,5f show the cylinder gauge simulation, whose bottom coordinate is (450,280,1) in the working volume. 15 steps, 200 sampling points are considered long cylinder axis, circumference direction, respectively. 150 mm radius, 300 mm length are considered. The radial error is shown in fig.5e, giving 59.56 μm bandwidth, and the axial error at the top surface is shown in fig.5f, giving 4.68 μm bandwidth.

7.Discussions and conclusions

The developed module for numerical simulation of CMM has been implemented on PC working environment. The main features of the module are as follows.

(1) A new method has been developed for the evaluation of length uncertainty, in which A,K, and B values can be evaluated efficiently using best fit lines among the the maximum data points ("envelope" points) in the plot of error vs. nominal length.

(2) A comprehensive step gauge simulation has been performed along all possible 3D, 2D, and 1D measuring lines in a working volume of CMM, which seems impossible in practical measurement with step gauge. the remarkable point here is that the length uncertainty along some representative measuring lines, which is currently recommended in national standards such as BS and VDI/VDE, gives just 70-90% of the length uncertainty along all possible 3D measuring lines in a working volume, where the length uncertainty along all possible 3D measuring lines seem to be closer to the real case of step gauge measurement.

(3) Random number generation module has been developed and incorporated into the random selection of measuring lines, giving very close results to the case of all possible measuring lines, with much less measuring lines considered.

(4) Ring gauge simulation has been implemented, and has been verified with cases of pure positional error and pure squareness error, showing good correlation with expected circular test ([7])

(5) The implemented sphere gauge simulation shows the influences of volumetric errors on the spherical surfaces, providing insight on behaviour of volumetric errors. In cases of pure squareness error and pure positional error, the sphere simulation turns out to be ellipsoidal form, as shown in fig.3d.

(6) The implemented cylinder gauge simulation can simulate a cylinder located anywhere and in any directions within the working volume, using transformation matrix. The axial error as well as radial error are evaluated and displayed.

(7) As all the modules have been implemented in high and low level language, such as PASCAL and ASSEMBLY language in PC environment, high level of user oriented modules are incorporated. Also, computer graphics library is installed in order to display all the error information on the computer screen, enabling plotting out through commercial plotters or any output devices.

(8) The module for geometric simulation can give great time saving for assessment of various geometric features such as step gauge, ring gauge, sphere gauge, and cylinder gauge, otherwise it would take long time or impossible to assess. The developed computer module, in conjunction with the volumetric error generator([5]), will bring great enhancement to assessments to various simulations of practical measurement tasks.

Acknowledgement

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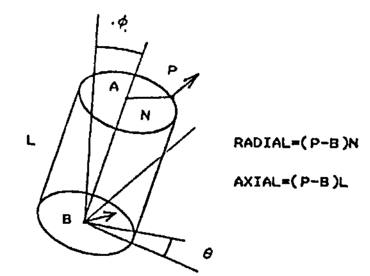


Fig.1 CYLINDER GEOMETRY

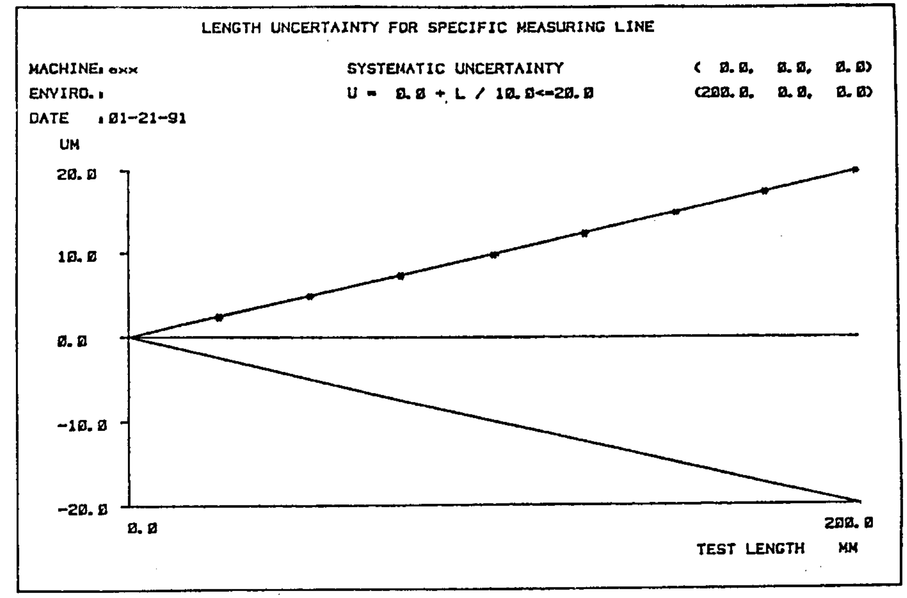
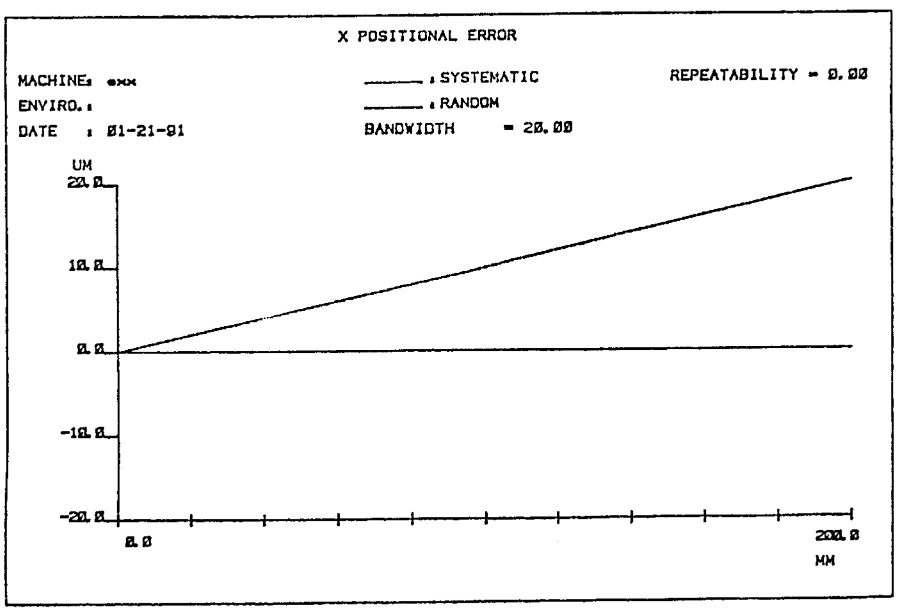


Fig.2b



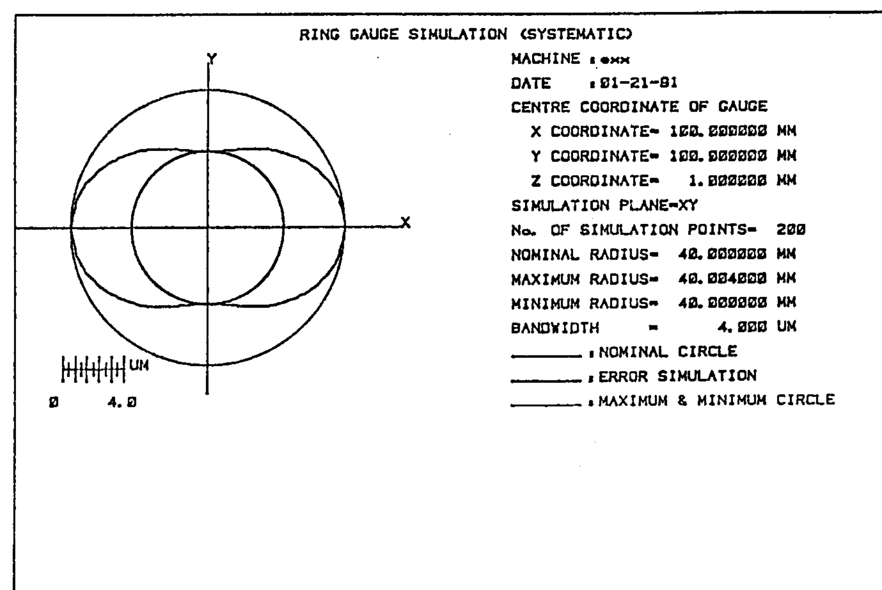


Fig.2c

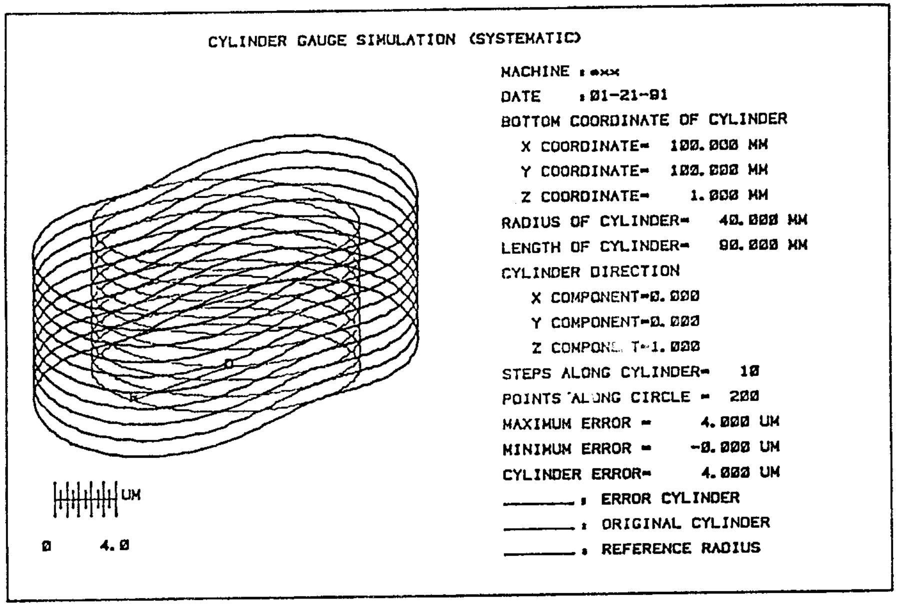


Fig.2d

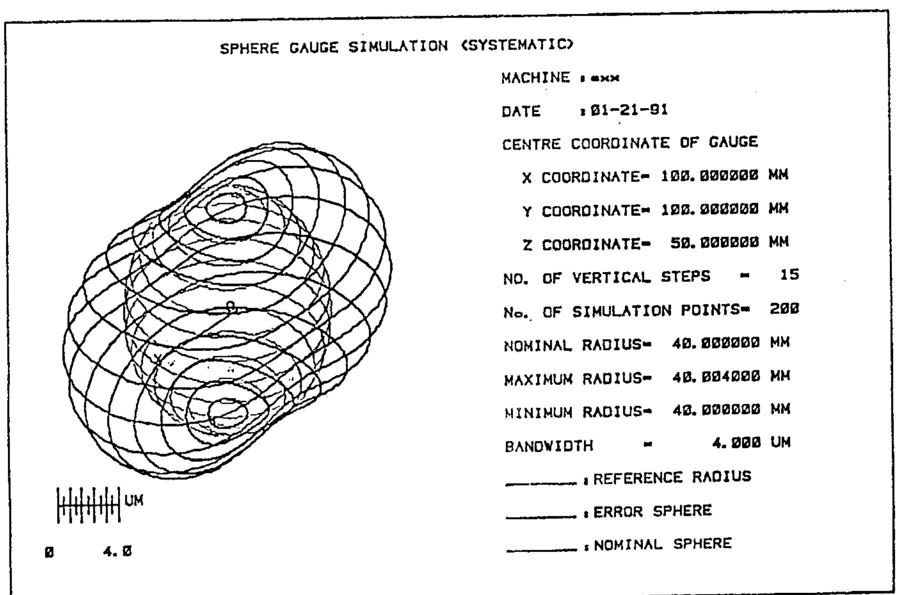


Fig.2e

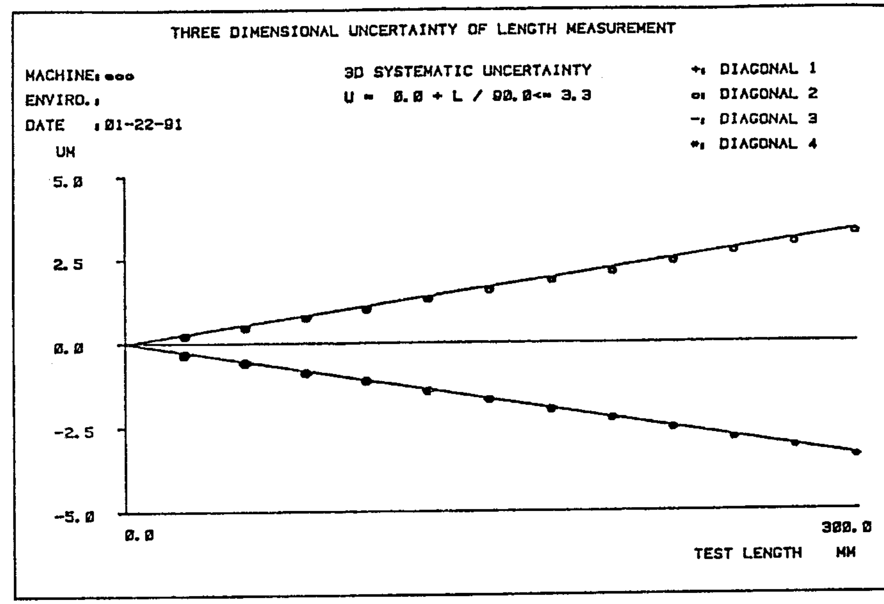


Fig.3a

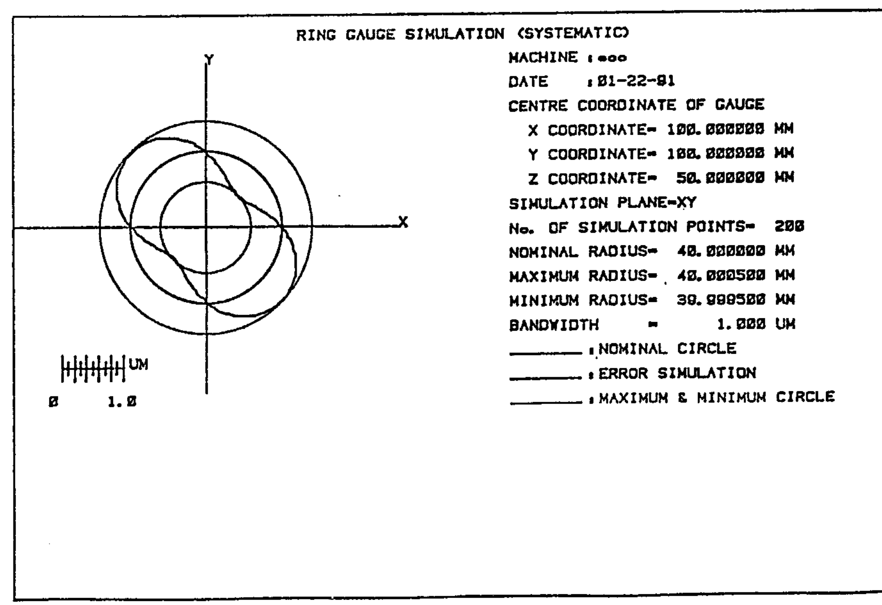
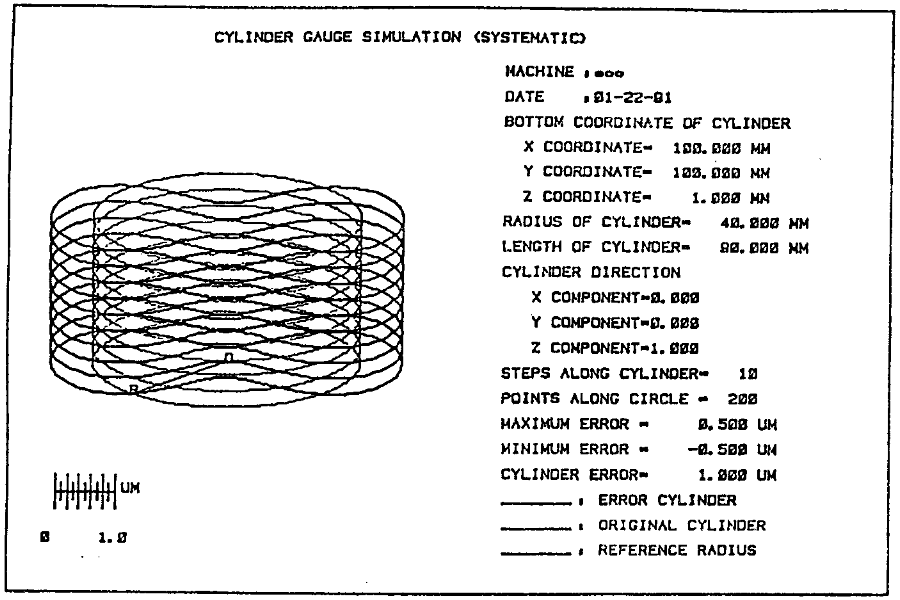


Fig.3b



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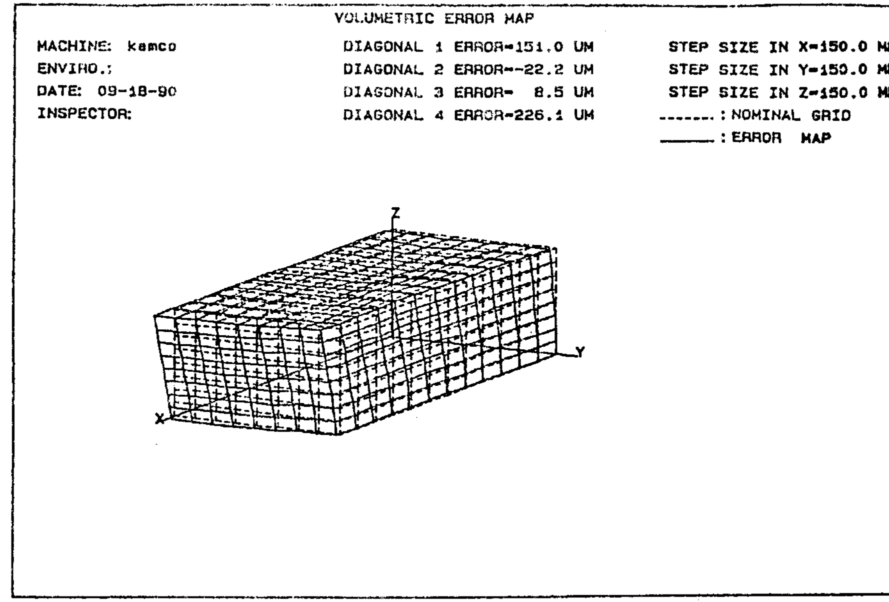

Fig.4a

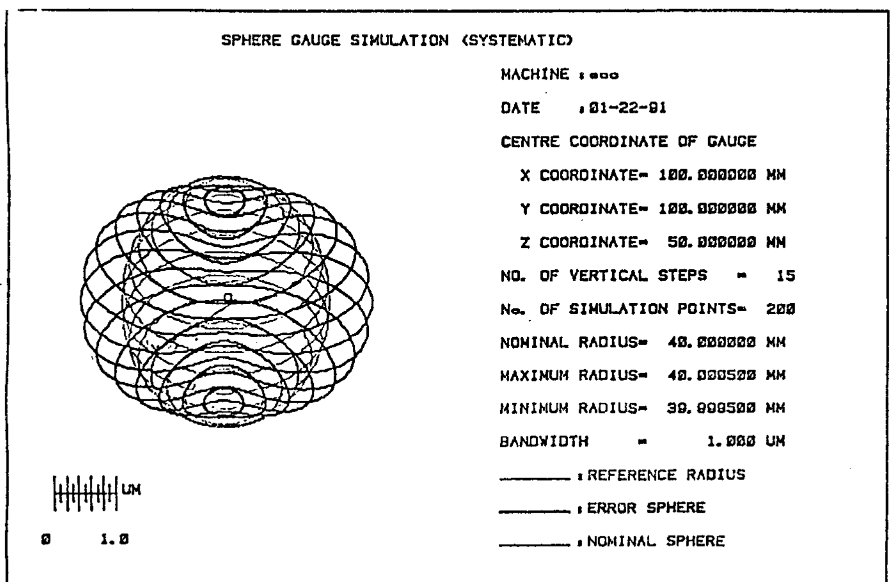

Fig.3d

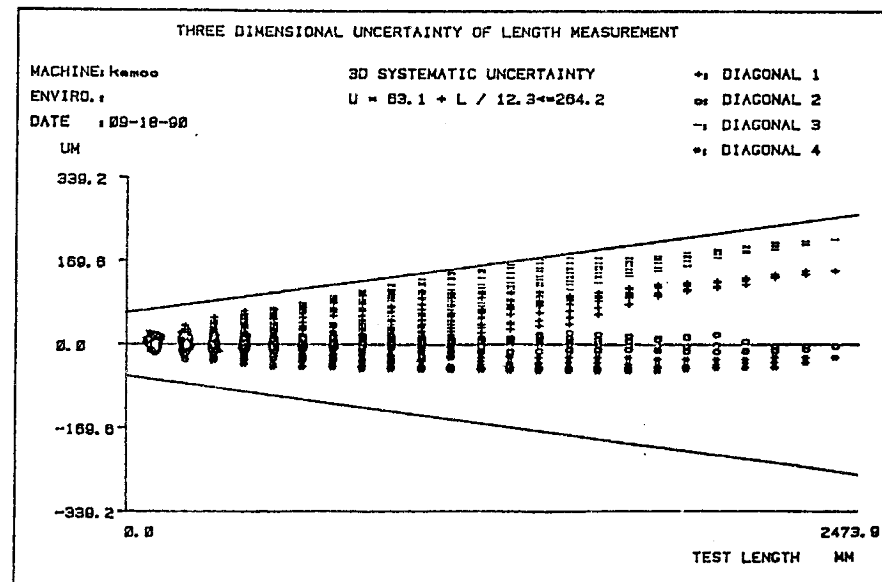

Fig.4b

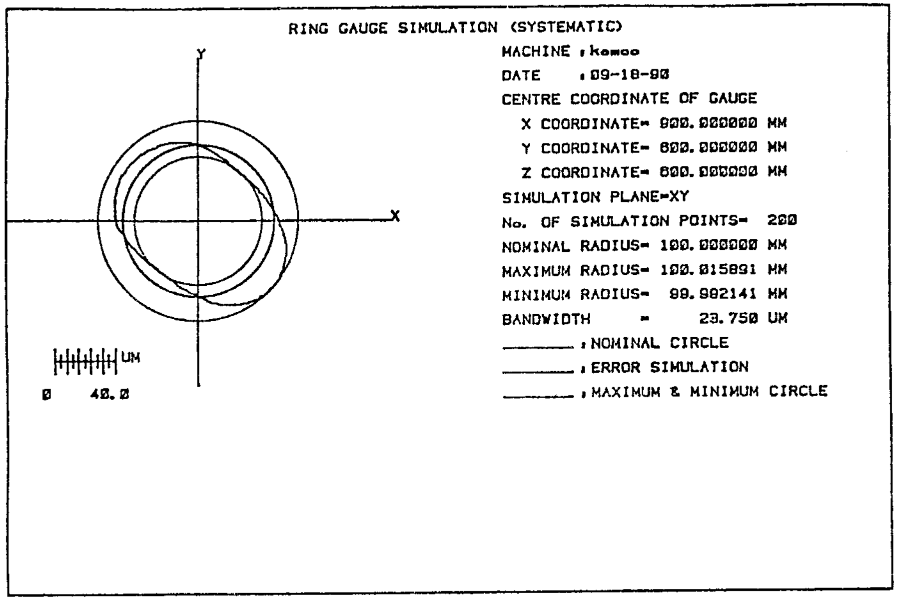

Fig.4c

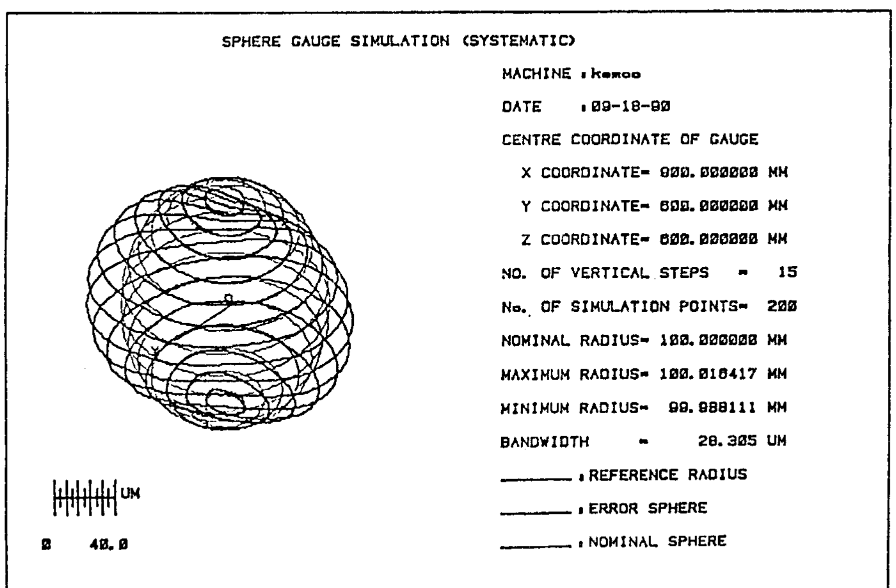

Fig.4d

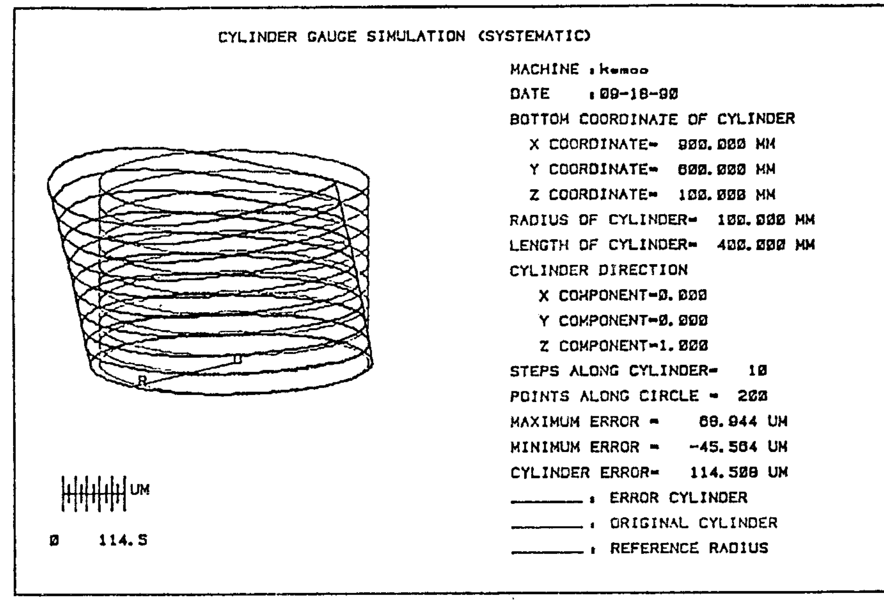

Fig.4e

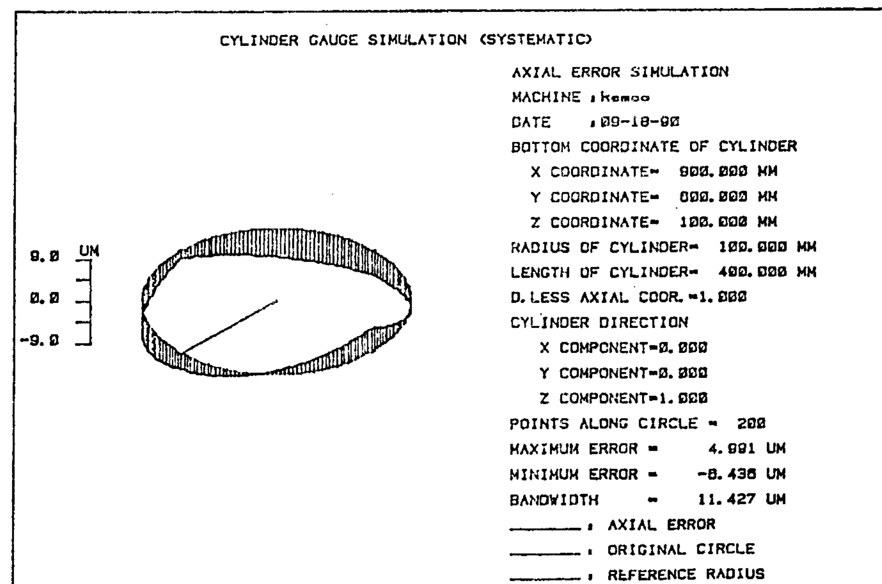

Fig.4f

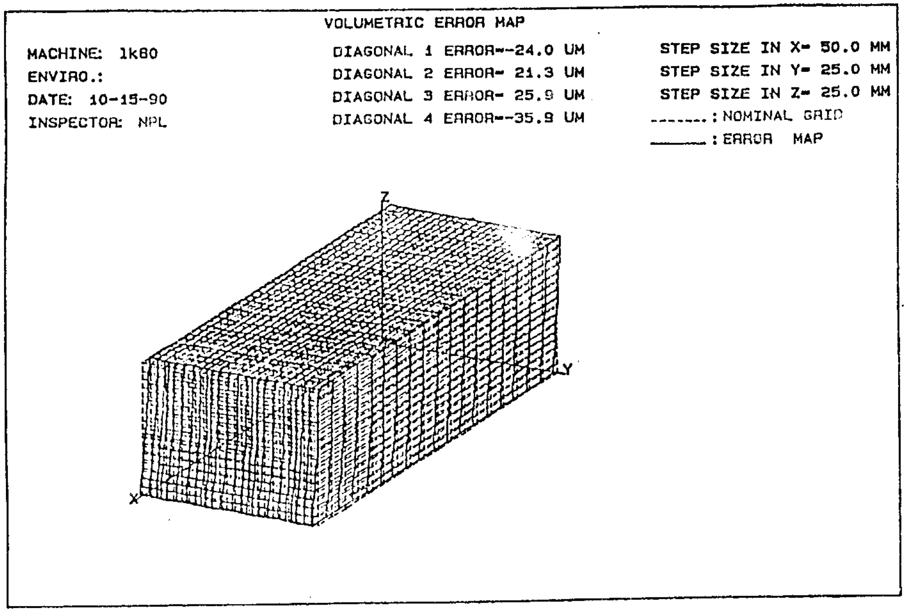

Fig.5a

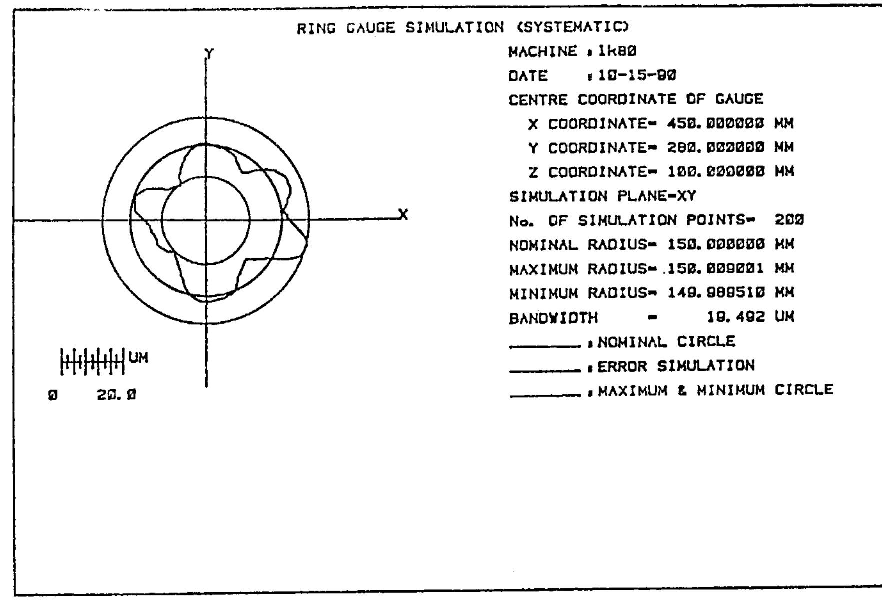

Fig.5c

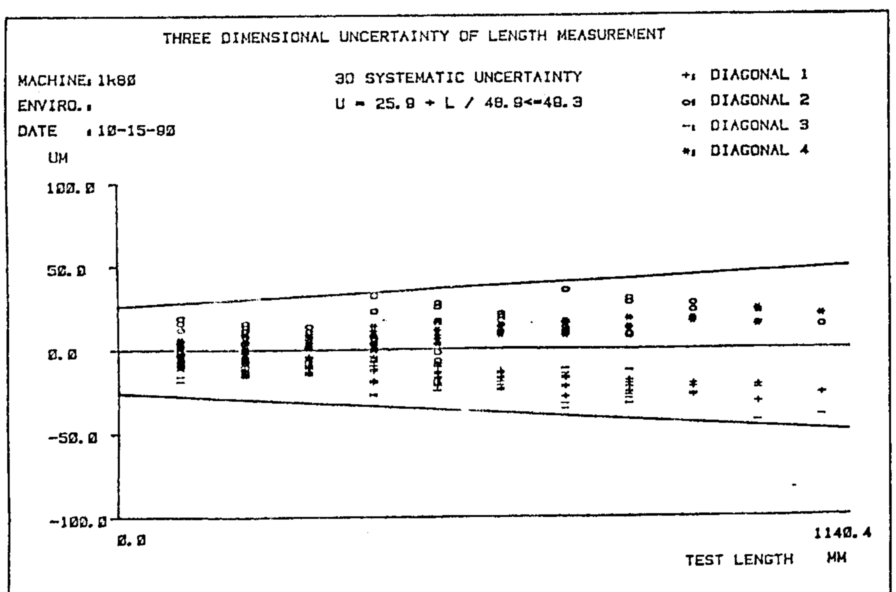

Fig.5b

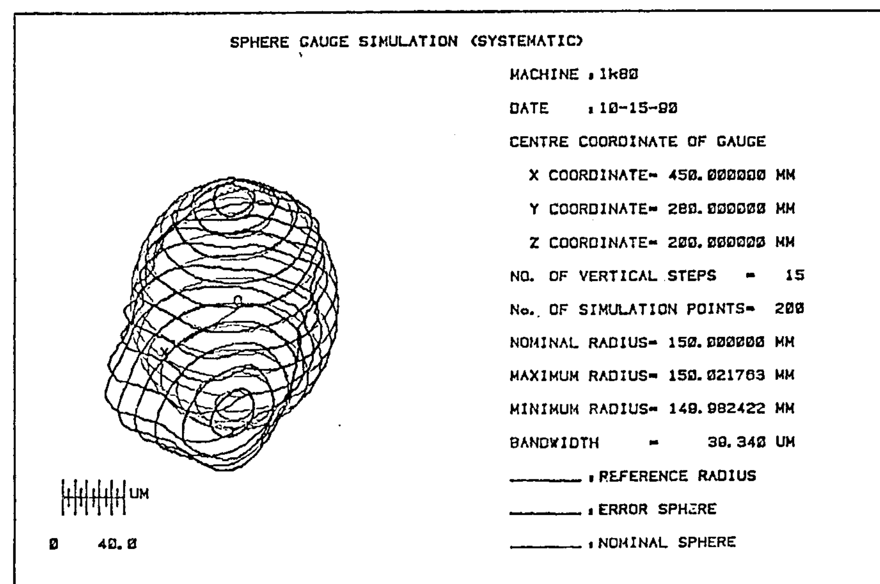

Fig.5d

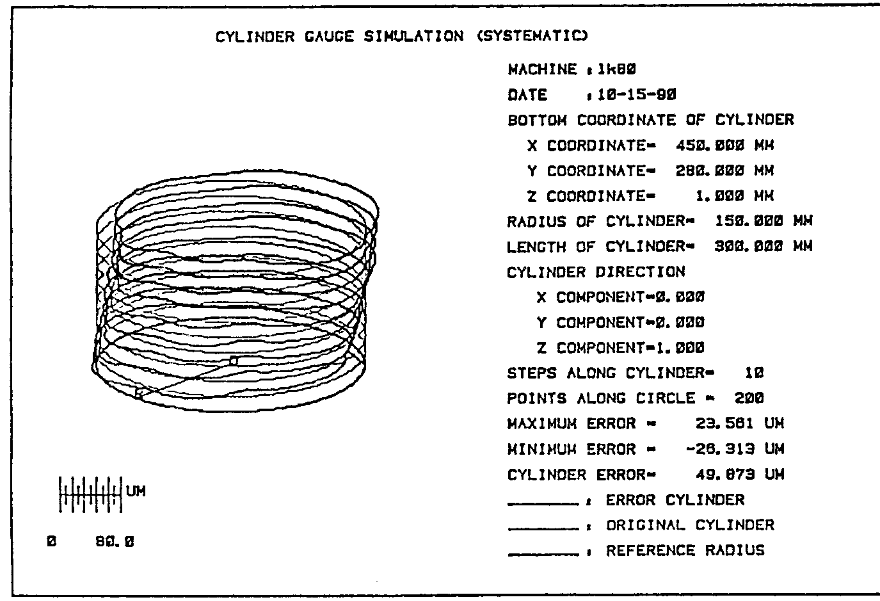
CYLINDER GAUGE SIMULATION (SYSTEMATIC)
MACHINE : 1k80
DATE : 10-15-90
BOTTOM COORDINATE OF CYLINDER
X COORDINATE= 450.000 MM
Y COORDINATE= 280.000 MM
Z COORDINATE= 1.000 MM
RADIUS OF CYLINDER= 150.000 MM
LENGTH OF CYLINDER= 300.000 MM
CYLINDER DIRECTION
X COMPONENT=0.000
Y COMPONENT=0.000
Z COMPONENT=1.000
STEPS ALONG CYLINDER= 10
POINTS ALONG CIRCLE = 200
MAXIMUM ERROR = 23.561 UM
MINIMUM ERROR = -26.313 UM
CYLINDER ERROR= 49.873 UM
: ERROR CYLINDER
: ORIGINAL CYLINDER
: REFERENCE RADIUS
UM
0 80.0

Fig.5e

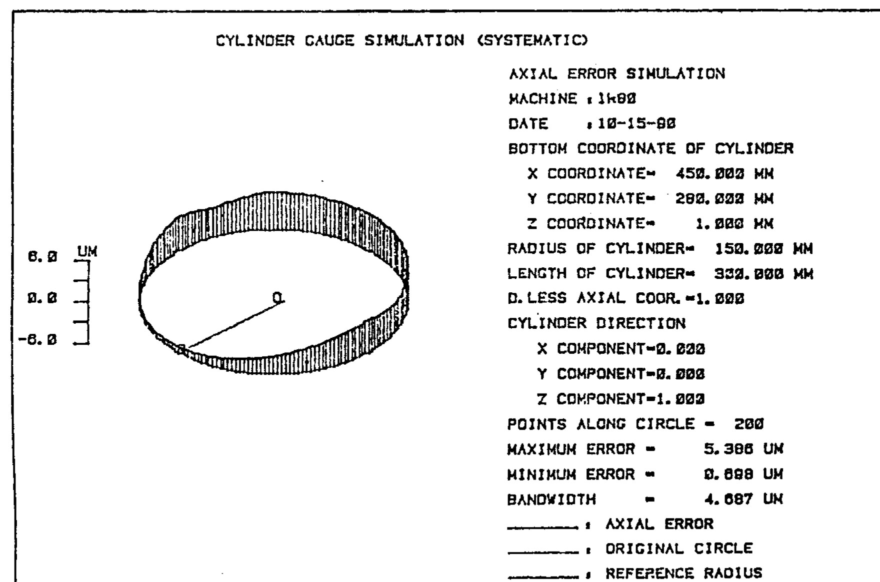
CYLINDER GAUGE SIMULATION (SYSTEMATIC)
AXIAL ERROR SIMULATION
MACHINE : 1k80
DATE : 10-15-90
BOTTOM COORDINATE OF CYLINDER
X COORDINATE= 450.000 MM
Y COORDINATE= 280.000 MM
Z COORDINATE= 1.000 MM
RADIUS OF CYLINDER= 150.000 MM
LENGTH OF CYLINDER= 300.000 MM
D.LESS AXIAL COOR.=1.000
CYLINDER DIRECTION
X COMPONENT=0.000
Y COMPONENT=0.000
Z COMPONENT=1.000
POINTS ALONG CIRCLE = 200
MAXIMUM ERROR = 5.386 UM
MINIMUM ERROR = 0.698 UM
BANDWIDTH = 4.687 UM
: AXIAL ERROR
: ORIGINAL CIRCLE
: REFERENCE RADIUS
6.0 UM
0.0
-6.0

Fig.5f